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# VERTICAL ARRAY TELESEISMIC SIGNAL MEASUREMENTS

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EARTH SCIENCES DIVISION  
TELETYPE INDUSTRIES, INC.

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VERTICAL ARRAY TELESEISMIC SIGNAL MEASUREMENTS

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### ABSTRACT

This is a signal study to demonstrate the possibility of reducing near surface reverberations due to geological effects near the vertical array receivers. The signals are deghosted to make the up-going P-pulses appear similar on all of the vertical array sensors. A correlation record is computed to measure the similar component which occurs jointly on all of the array elements. The coda of a strong USC&GS zero focus event and 588 km focus event were considerably simplified. The coda of a USC&GS 60 km event from the Aleutians showed sufficient definition to improve the detection of pulses occurring after the first P-pulse. Ten unobservable weak signals were processed and three were detected, based on proximity to Herrin times, amplitude and character.

## 1. INTRODUCTION

The concept of a vertical array is to record simultaneously on several transducers which are stacked in a deepwell which is 3 km or more in depth. We are interested in recording teleseismic events in the period range between .5 to 1.5 seconds. This is equivalent to about one-half to one-and-a-half wavelengths in the period range of interest. Ideally, we want to place instruments at one-fourth wavelength separation at the shortest wavelength of interest, which would be approximately .5 to .7 km apart. For our data, we use four deepwell instruments between 1½ and 3 km and one instrument near the surface. This is a good configuration based on the above criteria. The instruments are run on the same gain Geotech (1965), which makes convenient the design of detectors based on the combination of two or more seismometers. In addition, new developments beyond the scope of this report include a stacked array of triaxial seismometers described by Shappee and Douze (1966).

Although there is little background literature for this kind of operation, we can take advantage of years of experience in reflection seismology, where vertical stacking of an explosion source is used to remove distortion of near surface layering, mainly the ghost reflection from the surface. By appropriately scaling the frequencies, the stacked source array in reflection prospecting is equivalent to a maximum source depth of .07 km. This indicates close correspondence in wavelengths between our vertical array seismometer experi-

ments and the stacked source experiments in reflection prospecting. It is reasonable to anticipate similar results and to employ similar data processing schemes. By reciprocity, the same algorithms developed for stacked sources can be applied to stacked receivers by reversing the sign of the reflection coefficients. Goupillaud (1960) and Geotech (1965) apply inverse filtering to remove the effect of the surface and interbedded reflections. Various authors have developed techniques for the elimination of ghost arrivals interfering with the up-going compressional wave. Among these are Schneider, et al., (1964), Hammond (1962) and Lindsay (1960). The processing schemes differ in the amount of detail required in specifying the transmission properties over the span of the array, in the required control of source intensity or instrument gain, and the required amount of time, stability, and accuracy of computer processing. To design a feasible and robust processing scheme we attempt to minimize the dependency of our scheme on all of these requirements. The processing is designed to correct strong signal measurements for reverberation effects of layers near the surface at the receiver depths. We also investigated the possibility of improving the detection of weak p-waves through processing vertical array measurements.

### 1.1 Physical Description of Array

The vertical deepwell array at Apache, Oklahoma (Geographic Coordinates -  $34^{\circ}49'59.0''$  N and  $98^{\circ}26'09.0''$  W) consists of five Geotech Model 11167 seismometers. (The code identification and operating depth of each instrument is

listed alongside of its respective trace in figures appearing later in this report). The stratigraphic and velocity profiles were obtained from Geotech (1964). Basically, the region surrounding the AP-OK array consists of high-velocity limestones ( $v \approx 6$  km/sec) overlying an igneous basement complex having velocities in the neighborhood of 5 km/sec.

Field measurements on selected days, e.g., during June of 1965, were phased for an up-going P-pulse by recording the data with magnetic heads adjusted to compensate for the delay in the first arrival of the pulse. Data processing was designed to handle both kinds of recordings, the phased and normal un-phased recordings.

## 1.2 Description of Data Samples

Seismic data was selected from 17 June 1965, when instrument phasing was done and from 15 July 1965, in which normal non-phased seismic recordings were taken. Deepwell #5 (DW5), located at 50 feet below the earth's surface, was used in place of the surface trace. It resembled very closely the waveform at the surface recorded on the SPZ instrument. Furthermore, DW5 was at the same gain settings as the other deepwell seismometers, whereas the surface trace was not.

Samples were selected to demonstrate events having different focal depths and different apparent frequencies. Three events were processed with all aspects of the processing displayed. In addition, ten other small events were processed to demonstrate any large increase in detection capability for a vertical array processor. For these, only the surface

measurement, sum trace, and correlation traces are displayed for comparison. Table 1 briefly describes the events selected.

### 1.3 Data Processing

Before developing the deghosting technique, the deepwell trace was simulated from a surface seismogram. If a deepwell trace can be simulated by adding only an echo from the surface, it seems entirely plausible that by removing the ghost reflection from the deepwell trace, the up-going P-pulses can be made to appear similar at each depth. The echo-time delays for the four deepwell instruments are illustrated in Table 2. These were computed from the acoustic log vertical velocity profile, using an incidence angle of  $15^{\circ}$ , and were adjusted slightly by trial and error to obtain the best apparent results.

<u>INSTRUMENT</u>	<u>DEPTH (Ft.)</u>	<u>ECHO-TIME DELAY (Sec.)</u>
DW1	9454	.95
DW2	7460	.80
DW3	6465	.75
DW4	5456	.55

Table 2

<u>EVENT</u>	<u>ORIGIN TIME</u>	<u>USC&amp;GS FOCAL DEPTH (kml)</u>	<u>MAGNITUDE</u>	<u>ARRIVAL TIME</u>	<u>DISTANCE (°)</u>	<u>DATE</u>
Aleutians	19:05:9.1	67	5.2	19:15:20.3	61.5	6/17/65
Philippines	18:33:29.9	588	5.8	18:51:17.9	121.9	7/15/65
Kazakh SSR	03:44:58.2	0	5.4	03:58:26.5	95.5	6/17/65
Small 1	---	---	4.6	03:11:36.1	92.7	6/17/65
Small 2	---	---	4.1	04:56:13.9	96.3	6/17/65
Small 3	---	---	4.2	05:57:01.3	97.1	6/17/65
Small 4	---	---	3.8	08:35:00.2	80.5	6/17/65
Small 5	---	---	3.8	09:19:02.7	78.7	6/17/65
Small 6	---	---	3.9	10:15:39.9	25.9	6/17/65
Small 7	---	---	3.8	14:07:59.7	39.1	6/17/65
Small 8	---	---	4.0	14:31:51.0	48.1	6/17/65
Small 9	---	---	3.8	17:42:56.5	59.5	6/17/65
Small 10	---	---	4.9	19:15:15.4	61.5	6/17/65

Table 1. Description of Events Used to Measure Vertical Array Teleseismic Signals

Taking  $K$  as the number of digital points in the echo, assuming a trial reflection coefficient,  $\alpha$ , (0.9 was used) and given the surface or near surface trace  $X_i$ , the phased simulated deepwell trace is

$$Z_i = X_i + \alpha X_{i-K}$$

The normal non-phased simulated deepwell trace is

$$Z_i = X_i + K/2 + \alpha X_{i-K/2}$$

For simulation, the ghost is constructed from the surface reflected P-pulse. The surface reflected S-pulse and other reflected pulses are neglected.

#### 1.4 Deghosting - Method I

When a surface or near surface trace is available, the deghosted trace can be constructed by simply shifting the surface trace by  $K$ , multiplying by  $\frac{1}{2}\alpha$ , and subtracting this resultant from either the deepwell trace (phased vertical array) or the deepwell trace shifted by  $K/2$  (non-phased vertical array). For phased vertical array measurements, the echo or ghost is removed on  $Z$ ,

$$Z_i = Y_i - \frac{1}{2}\alpha X_{(i-K)}$$

and for non-phased or normal deepwell records,

$$Z_i = Y_{(i-K/2)} - \frac{1}{2}\alpha X_{(i-K)},$$

where X, Y, and Z are the surface, deepwell, and deghosted deepwell, respectively.

If a surface trace is not available, the ghost can be removed by an inverse filter, as developed in the next section.

### 1.5 Deghosting Method II

It would seem more plausible to develop a deghosting process that removes the echo without the use of a surface seismogram, a practical technique that would figuratively push the ghost off the end of the deepwell trace.

Given the reflection coefficient  $\alpha$ , and the deepwell trace  $Y_{i,1}$  the phased deghosted trace is formed as follows: First a new trace  $Z_{i,1}$  is defined to be

$$Z_{i,1} = Y_{i,1} - X_{(i - NT_1)} \cdot \alpha_1,$$

where  $NT_1$  is equal to the product of the sampling rate and the echo time delay (K). This above equation simply shifts and inverts the ghost to a point  $NT_1$  farther down the seismic record than it originally was.  $\alpha_1$  is redefined as  $\alpha_2 = \alpha_1^2$  and  $NT$  is redefined to be,  $NT_2 = 2 \cdot NT_1$  and a new trace  $Z_{i,2}$  is formed where,  $Z_{i,2} = X_{i,2} + X_{(i - NT_2)} \cdot \alpha_2$ . Here the ghost is inverted and shifted still farther ( $NT_2$  points) down the seismic record. This iterative process is continued until the ghost reflection is pushed off the seismic record.



In general

$$Z_{i,j} = X_{i,j} + X_{(i - NT_j) \alpha_j}, \text{ where } \alpha_{j+1} = \alpha_j \cdot \alpha_j,$$

$NT_{j+1} = 2 \cdot NT_j$ , and  $NT_j \leq N$  (The number of data points in the deepwell trace). (Refer to Appendix I for complete discussion of Z-transform).

For non-phased deghosting, the same technique, as that developed above, applies except the final deghosted trace is time-shifted by  $K/2$  to the right in order to align the deepwell with the surface trace.

### 1.6 Vertical Velocity Filtering

(a) Phased sum of vertical array - The phased sum of the vertical array is formed by merely adding all traces point by point. That is

$$S_j = \sum_{i=1}^N X_{i,j}$$

where  $i$  is an index which numbers the sensors and  $N$  is the number of seismometers in the set of vertical arrays  $X_{i,j}$ .

(b) Phased sum of deghosted vertical array - The same formula applies for the deghosted phased sum  $S_i$ , except  $X_{i,j}$  is the set of deghosted vertical arrays.

(c) Multi-channel minimum variance estimate of a signal fixed on all elements of the vertical array - The formula for the correlation trace is,

$$X_i = \langle \dots \langle \langle X_1 X_2 \rangle X_3 \rangle \dots X_J \rangle X_J \bigg/ \prod_{j=2}^J \langle X_{i,j} X_{i,j} \rangle$$

where J is the number of deepwell channels on the seismogram (refer to Appendix 2 for derivation), i is the number ordering the sequence of points on the time axis, and the symbol  $\langle \rangle$  represents smoothing with a moving taper or time window.

### 1.7 Discussion of Programs

The following eight digital programs are available to either remove the ghost reflection or simulate a deepwell trace:

1. PROGRAM SSIMDEEP works on a surface trace to simulate a phased deepwell seismic record. Given the echo times between the deepwell and the surface and further given the reflection coefficient, the phased deepwell trace is computed by SUBROUTINE SSIMGO. The sum traces of both the deep and simulated deepwell traces are computed. Plots are obtained of the deepwell seismogram, simulated deepwell seismogram, and the two above sum traces.
2. PROGRAM SGOSTSEI removes the ghost reflection when a surface or near surface trace is available at the same gain. Given the echo times and the reflection coefficient, the phased deghosted trace is computed by SUBROUTINE SDEGOSTE. The sum and correlation traces are also computed. Plots are obtained of each deepwell and simulated deepwell seismogram and their corresponding sum and correlation traces.

3. PROGRAM SDEGSEI removes ghost reflection on a deepwell seismogram with the use of SUBROUTINE SDEGOSTI, given only the echo-time and the reflection coefficient. Plots are obtained of deepwell and deghosted deepwell seismograms, sum traces and correlation traces.
- 4-6. PROGRAMS SIMDEEP, GOSTSEIS, and DEGSEIS work in place of 1, 2, and 3, respectively, when normal non-phased seismic data is used. Calls are made to SUBROUTINES SIMGO, DEGOSTE, and DEGOSTE1.
- 7-8. PROGRAMS SVARRAY and VARRAY are used on phased and non-phased data, respectively, in place of SDEGSEI and DEGSEIS when only plots of surface, deghosted sum, and correlation traces are wanted. A bandpass filter is applied to the input traces.

## 2. RESULTS

The events were selected to demonstrate measurements of signals of various types. The results of array processing are shown in the following figures:

- I shows the raw data measurements, phased sum, and phased correlation traces
- II compares the deepwell measurements to simulated deepwell measurement

- III shows the phased deepwell measurements deghosted by subtraction of the surface measurement and includes the sum and correlation traces
- IV shows the phased deepwell measurements deghosted by means of an inverse operator which removes the surface echo and includes the sum and correlation trace

The figure numbers are followed by a letter (such as II-B); the letter designates the event. The events are:

- A an Aleutian event with an extremely complex coda and focus of about 60 km, selected to demonstrate possible removal of the part of the complexity due to station reverberations to facilitate picking of multiple transmissions of P and depth phases
- B an event from the Philippines with a focus of about 600 km, selected to demonstrate improvement in the simplicity and reduction of false multiples in the coda
- C a simple event from Kazakh, with USC&GS focus at the surface

In Figures IA-IC, the apparent contrast between signal and noise appears to be greater at the surface than in the

ORIGINAL

DW1  
9454'

DW2  
7460'

DW3  
6465'

DW4  
5456'

SUM  
TRACE

DW5  
50'

CORRELATION  
TRACE

Figure I-A. Vertical Component Vertical Array Measurements--Aleutians,  
USCGS Focus 67 km, Magnitude 5.2, Date 6/17/65, Time 19:05:9.1

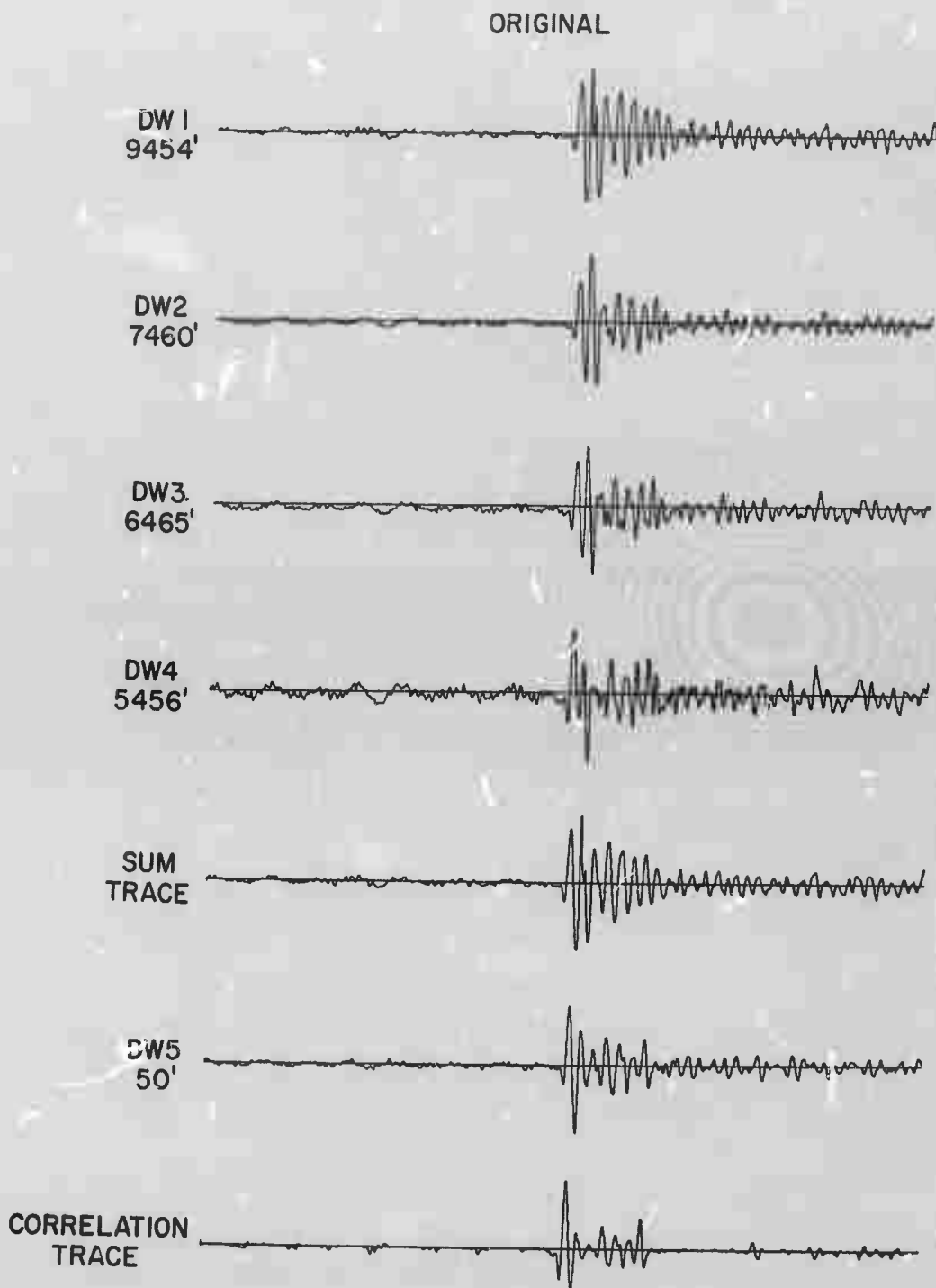


Figure I-B. Vertical Component Vertical Array Measurements--  
Philippine Islands, USCGS Focus 588 km,  
Magnitude 5.8, Date 7/15/65, Time 18:33:29.9

ORIGINAL

DW1  
9454'

DW2  
7460'

DW3  
6465'

DW4  
5456'

SUM  
TRACE

DW5  
50'

CORRELATION  
TRACE

Figure I-C. Vertical Component Vertical Array Measurements--Kazakh,  
USCGS Focus OKM, Magnitude 5.4, Date 6/17/65, Time 03:44:58.2

deepwell; the 6 second and .5 second noise is accentuated in the deepwell measurements. Based on these observations, AP-OK does not appear to be the best possible selection to show improvements by vertical array processing. All of the sum traces, phased for an upgoing vertical P-wave, appear to yield higher ambient and signal generated noise in contrast with the apparently visible signal phases. The correlation trace shows moderate improvement in signal contrast, with better definition of multiple arrivals and depth phases in Figure I A and considerable cleanup of the coda in Figures I B and I C.

Figures II A - II C demonstrate that the deepwell seismogram can be simulated from the surface trace by only considering the free surface reflection, and neglecting interbedded reflections. Since, for the forward problem of deriving the deepwell seismogram from the surface seismogram, it is adequate to consider only the P surface reflection, it then follows that in designing the inverse operator it is also adequate to consider only the free surface reflection. We note that the correspondence between deepwell measurements and the simulations is generally quite good, although a smaller uncorrelated component can be observed which can be attributed to interbedded reflections, scattering, etc. This component should also be uncorrelated between deepwell sensors and at least partially removed by the correlation trace.

Figures III A - III C and IV A - IV C allow us to compare two different methods for removing the surface echo. Method I shown on Figure III is conceptually simple and involves only subtracting the shifted surface trace to remove the echo.



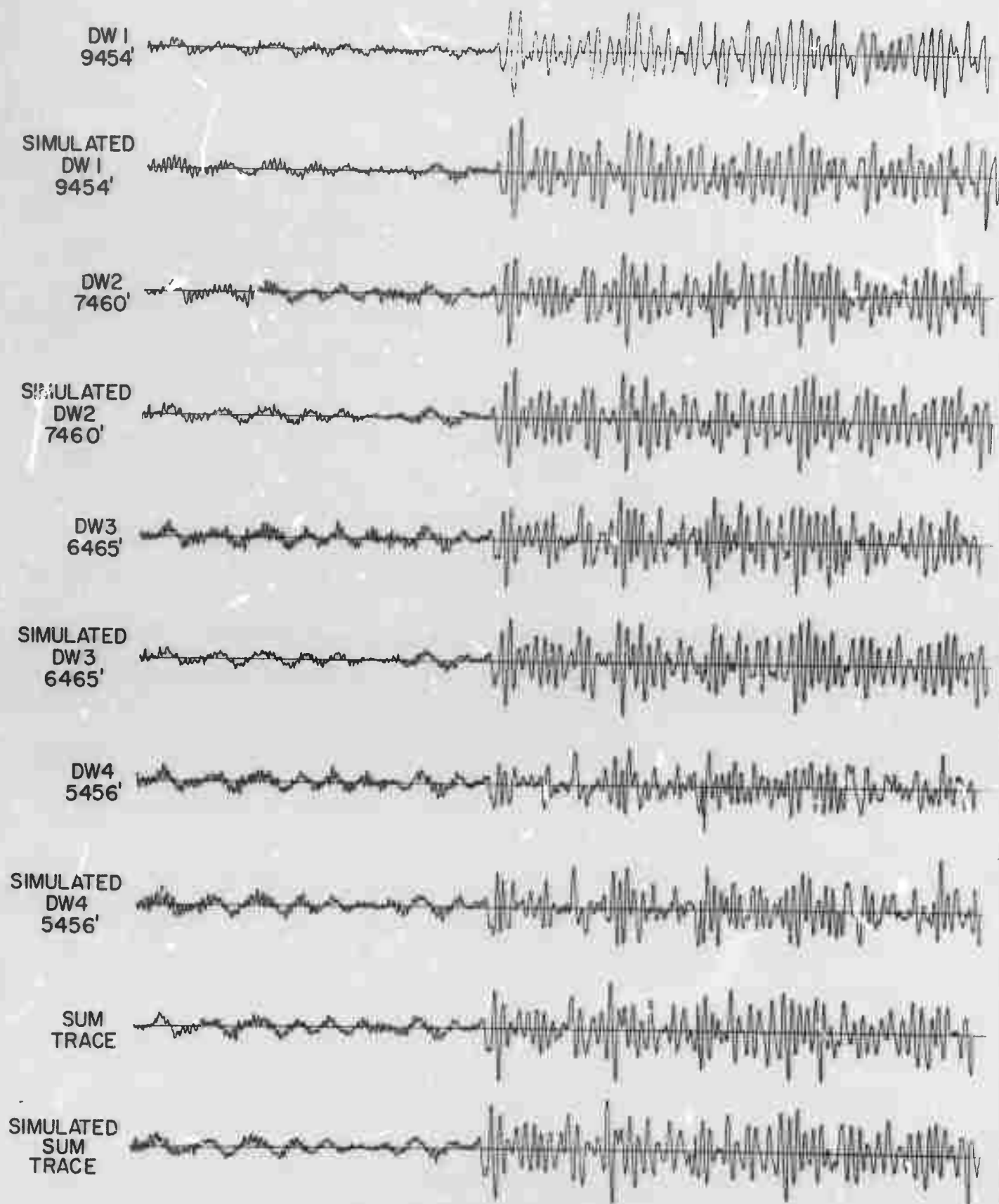


Figure II-A. Comparison of Deepwell and Simulated Deepwell Seismograms

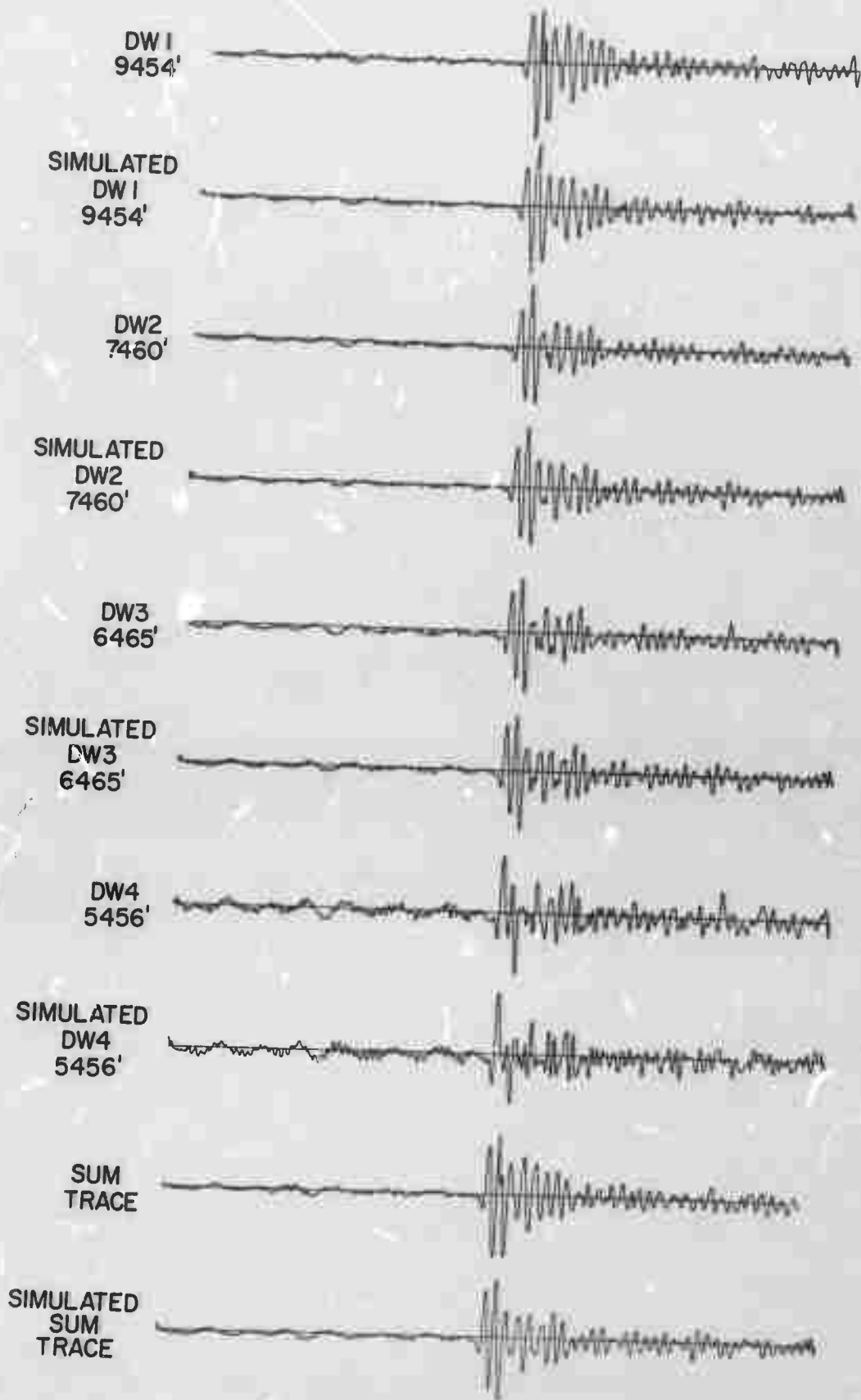


Figure II-B. Comparison of Deepwell and Simulated Deepwell Seismograms

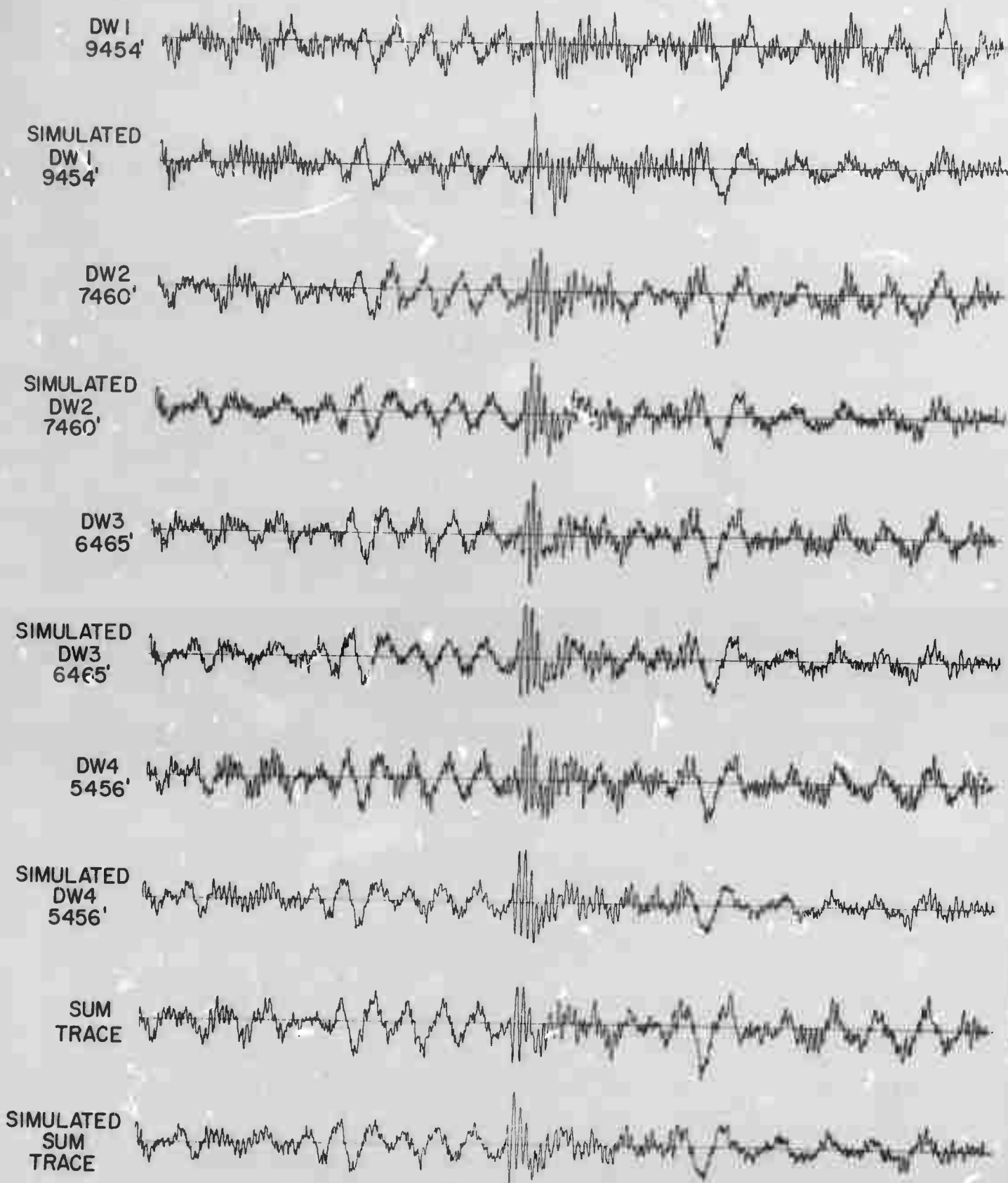


Figure II-C. Comparison of Deepwell and Simulated Deepwell Seismograms

DE-GHOSTED

DW1  
9454'

DW2  
7460'

DW3  
6465'

DW4  
5456'

SUM  
TRACE

DW5  
50'

CORRELATION  
TRACE

Figure III-A. Deghosted Vertical Array Measurements, Method I

DE-GHOSTED

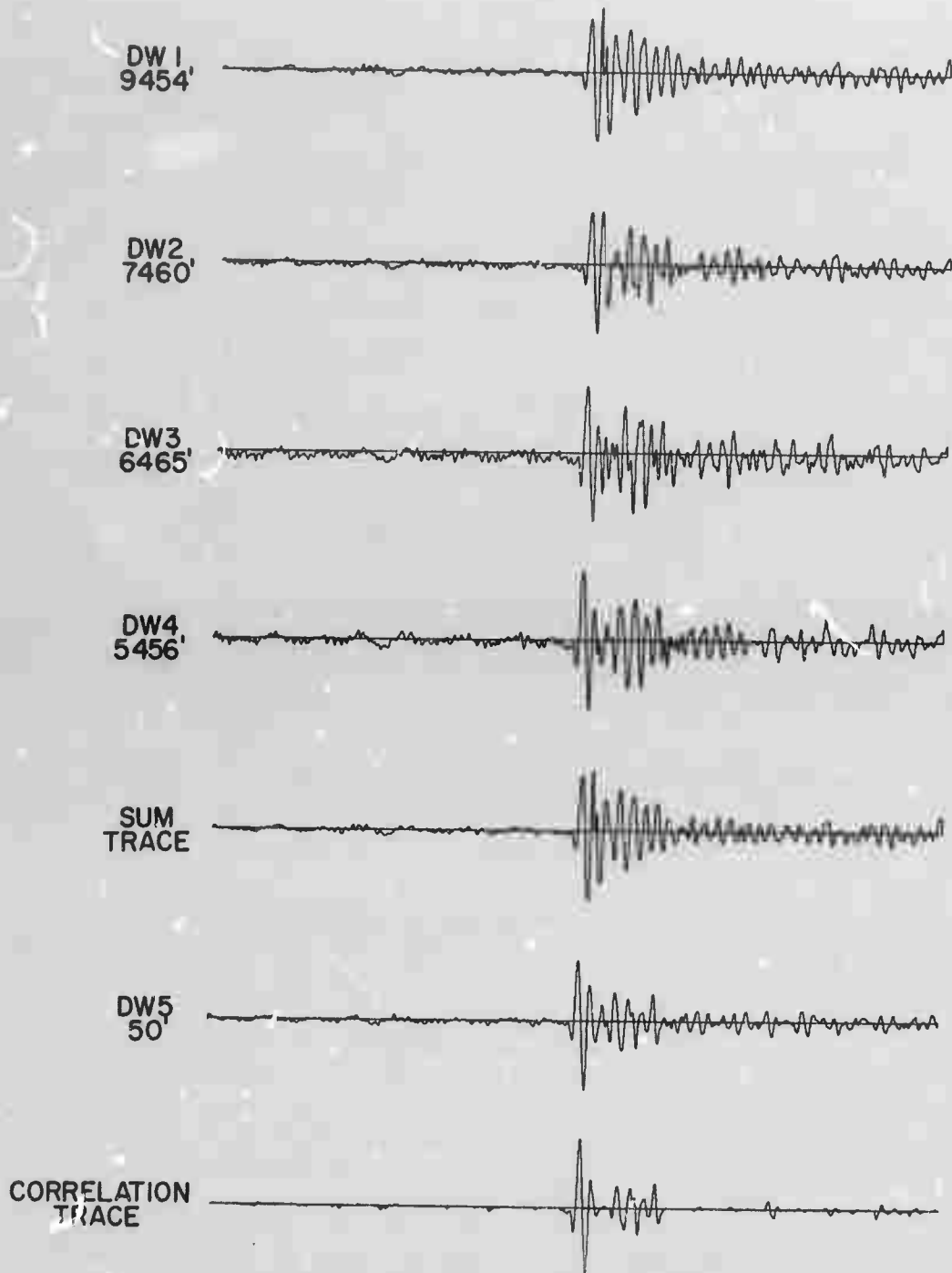


Figure III-B. Deghosted Vertical Array Measurements, Method I

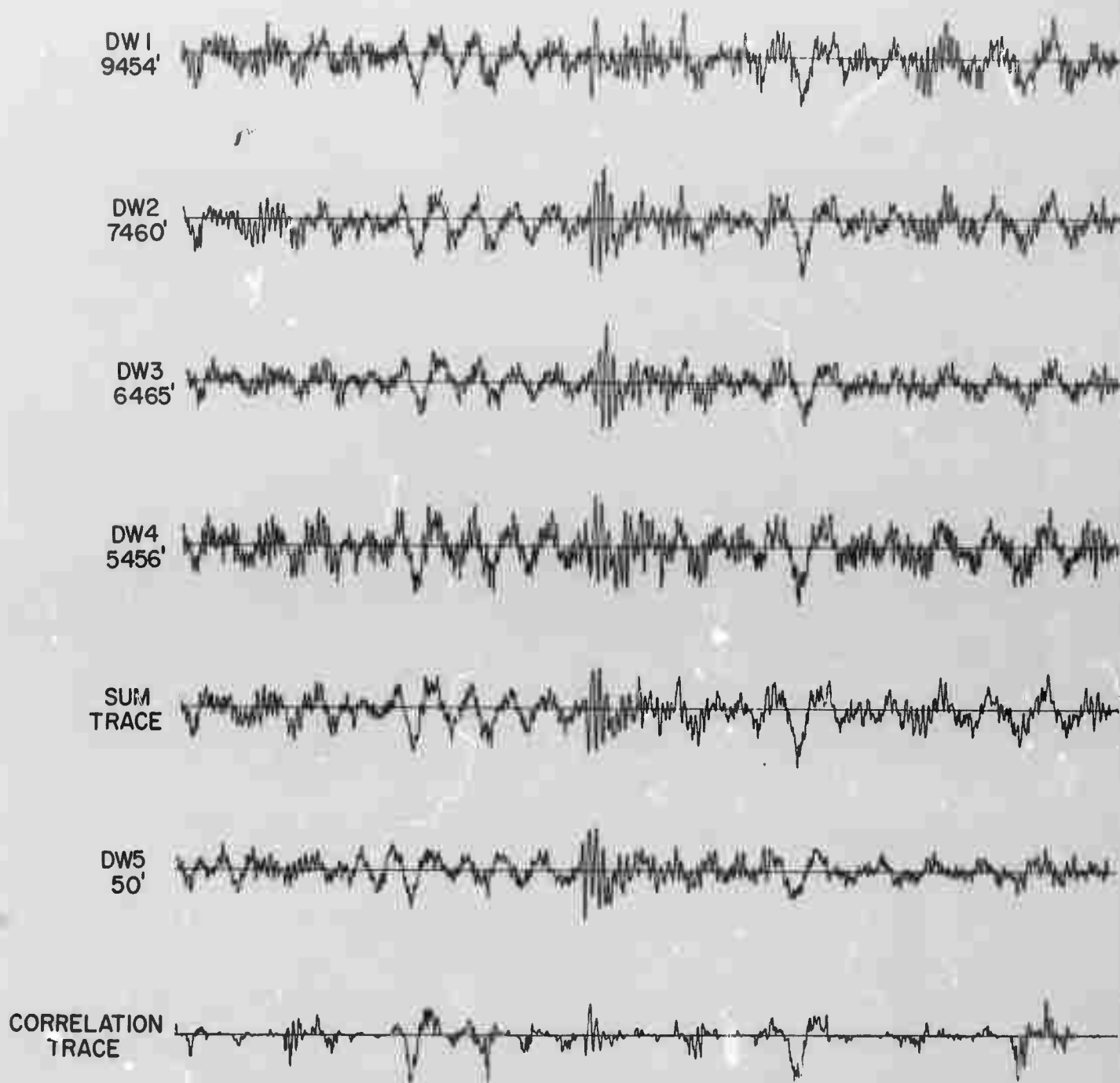


Figure III-C. Deghosted Vertical Array Measurements, Method I

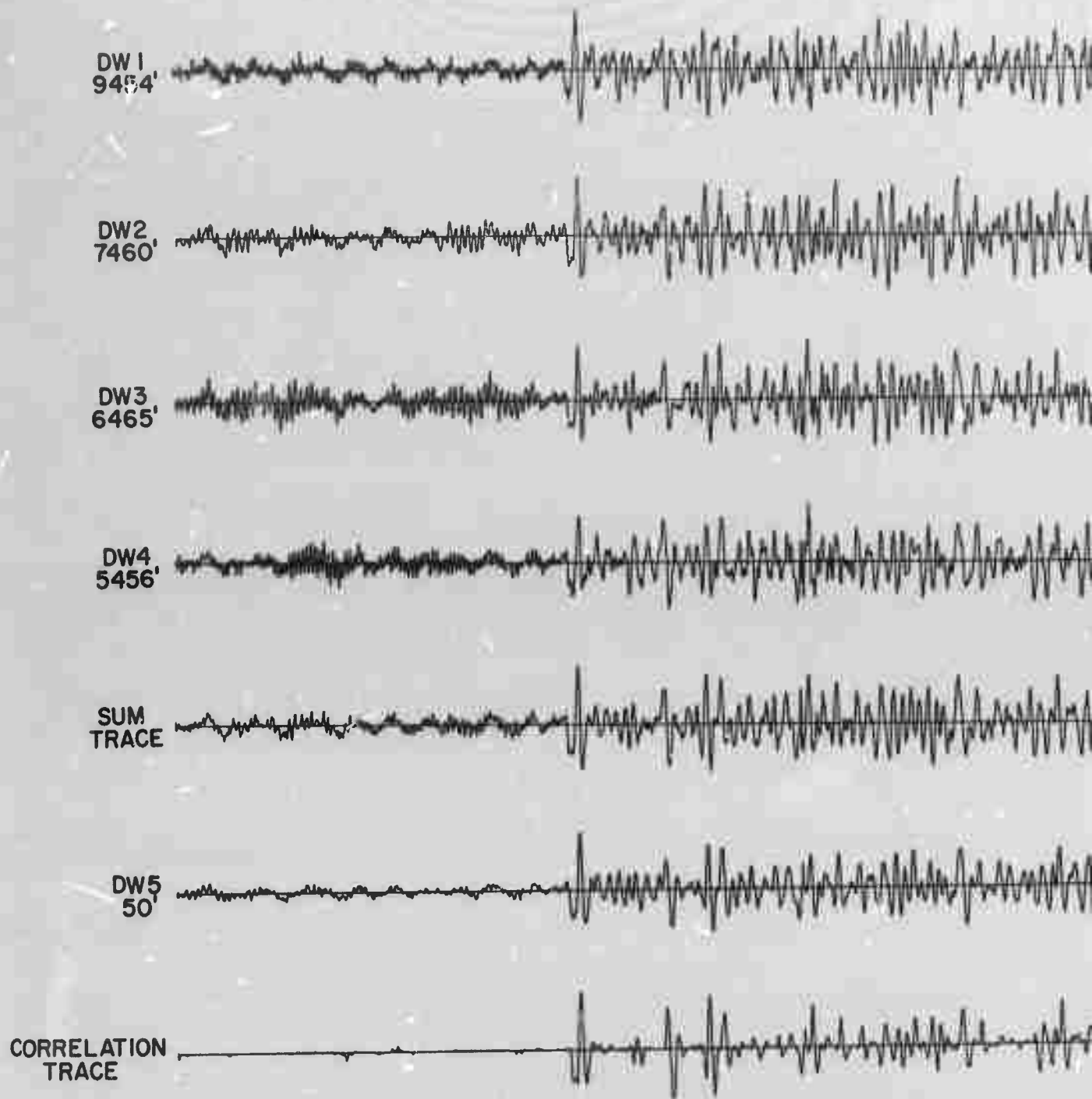


Figure IV-A. Deghosted Vertical Array Measurements,  
Method II (Reflection Coefficient 0.7)

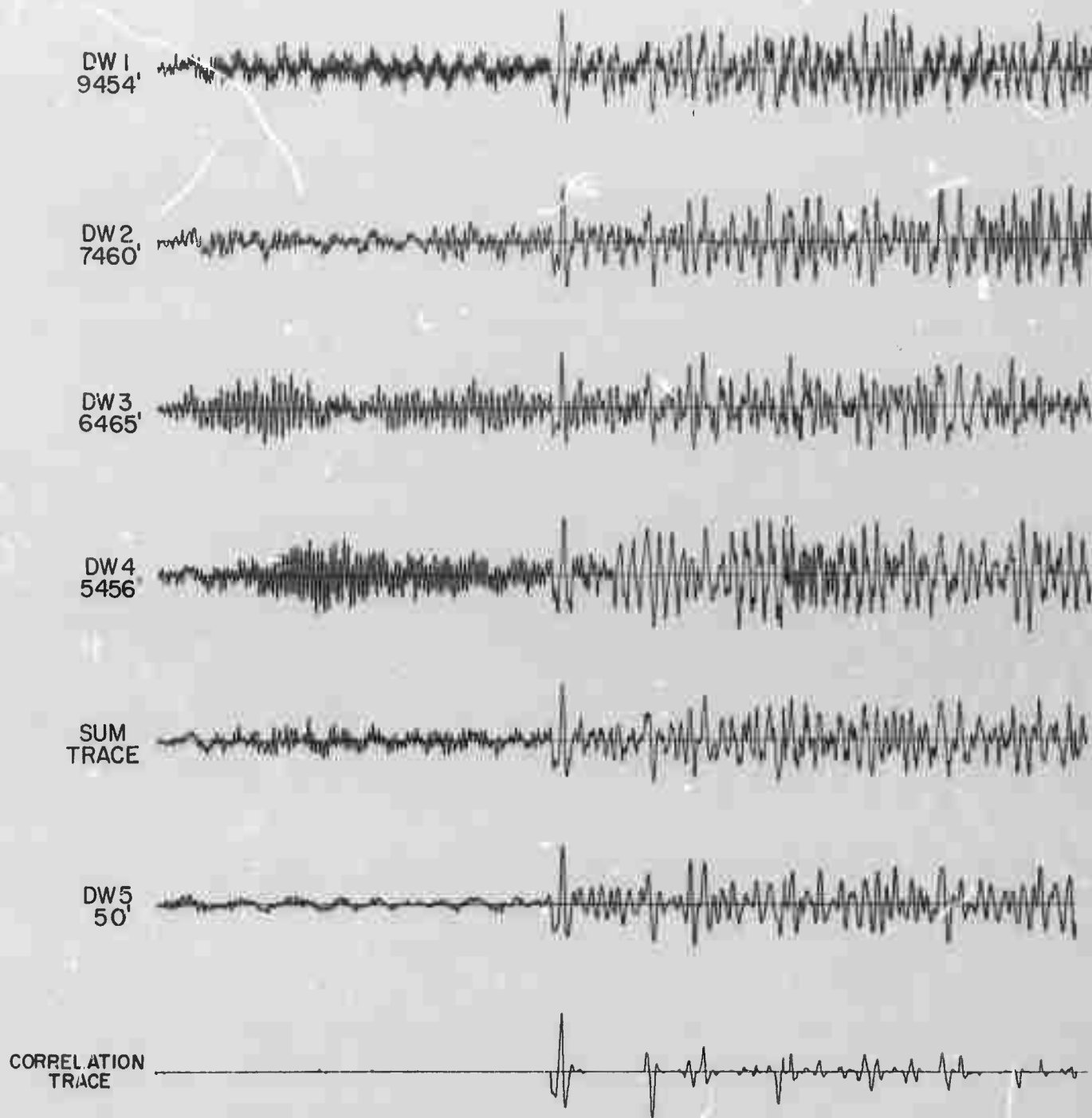


Figure IV-A-1. Deghosted Vertical Array Measurements,  
Method II (Reflection Coefficient 0.9)



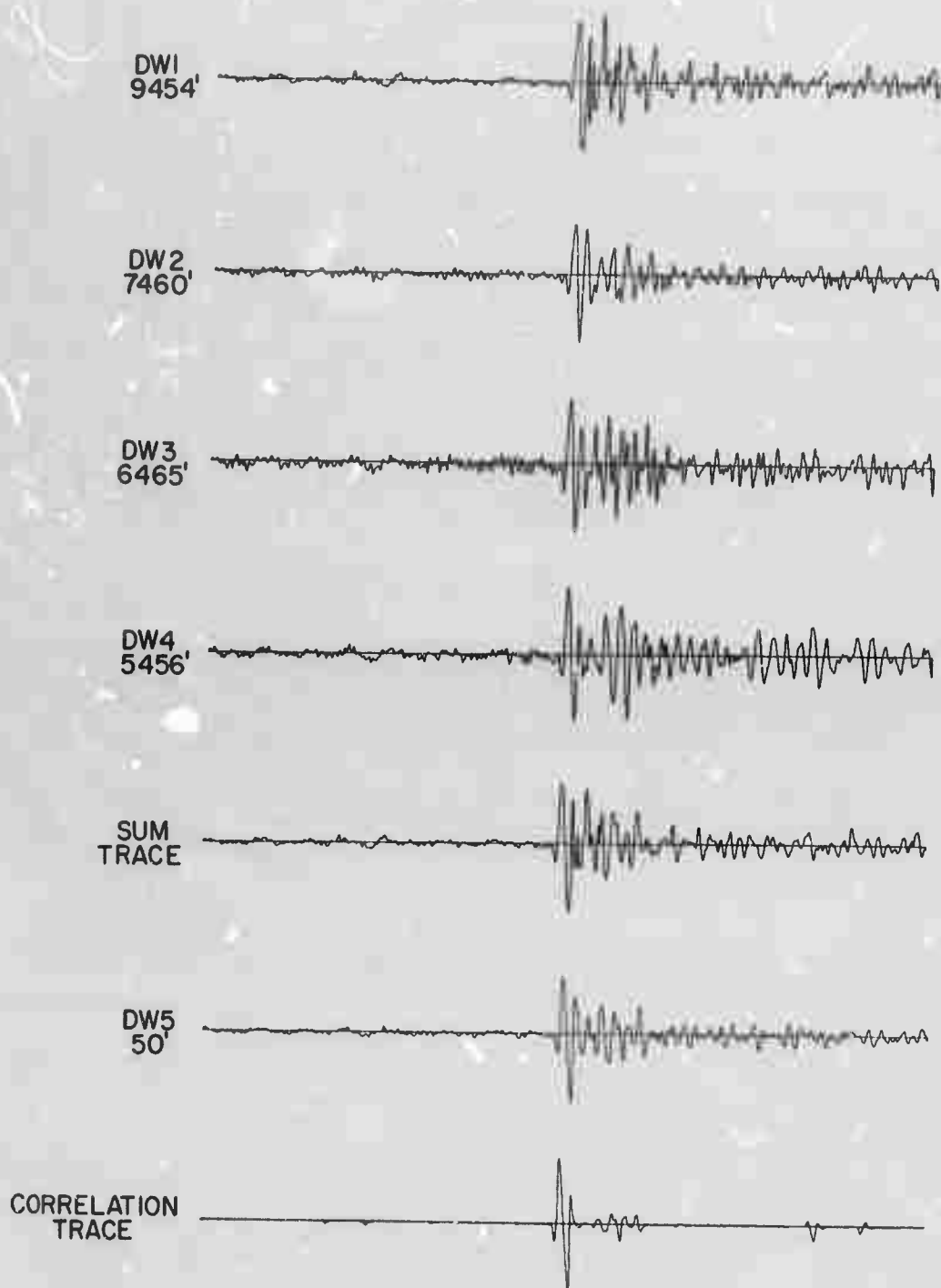


Figure IV-B. Deghosted Vertical Array Measurements;  
Method II (Reflection Coefficient 0.7 on all traces)  
Earthquake Philippine Islands, USCGS Focus 588 km,  
Magnitude 5.8, Date 7/15/65, Time 18:33:29.9

DW 1  
9454'



DW 2  
7460'



DW 3  
6465'



DW 4  
5456'



SUM  
TRACE



CORRELATION  
TRACE



DW 5  
50'



Figure IV-C. Deghosted Vertical Array Measurements,  
Method II (Reflection Coefficient 0.7)

Method II shown on Figure IV utilizes an inverse operator to remove the echo. Both methods do an adequate job; the correlation trace for Method II has a slightly cleaner coda and this method has the advantage of not requiring a quiet surface trace and exact control of instrument gain. Since the computation time of Method II is extremely fast, it is practical to utilize it for production computations of the correlation trace.

Figures V, VI, and VII show a sample of ten events for which we seek a preliminary demonstration of the detection capability of this vertical array. The events are unobservable with Herrin times indicated by an arrow. Figure V shows the surface measurements, Figure VI the deepwell deghosted phased sum measurements, and Figure VII the deghosted correlation trace. All of the above outputs are filtered with a broadband filter set at a center frequency of 1.25 cps. We consider the detection a success only if a phase appears clearly visible. The fraction of total events detected is 10% for the filtered surface trace, 0% for the phased sum, and 30% for the correlation trace.

### 3. CONCLUSIONS

Vertical array processing, based on previous experience with stacked sources, appears, as expected, to be an effective means of reducing the reverberations and complexity of the coda caused by near surface reverberations at the receiver. As to increasing the detectability of weak P-pulses based on nearly isotropic vertical velocity filtering, the preliminary

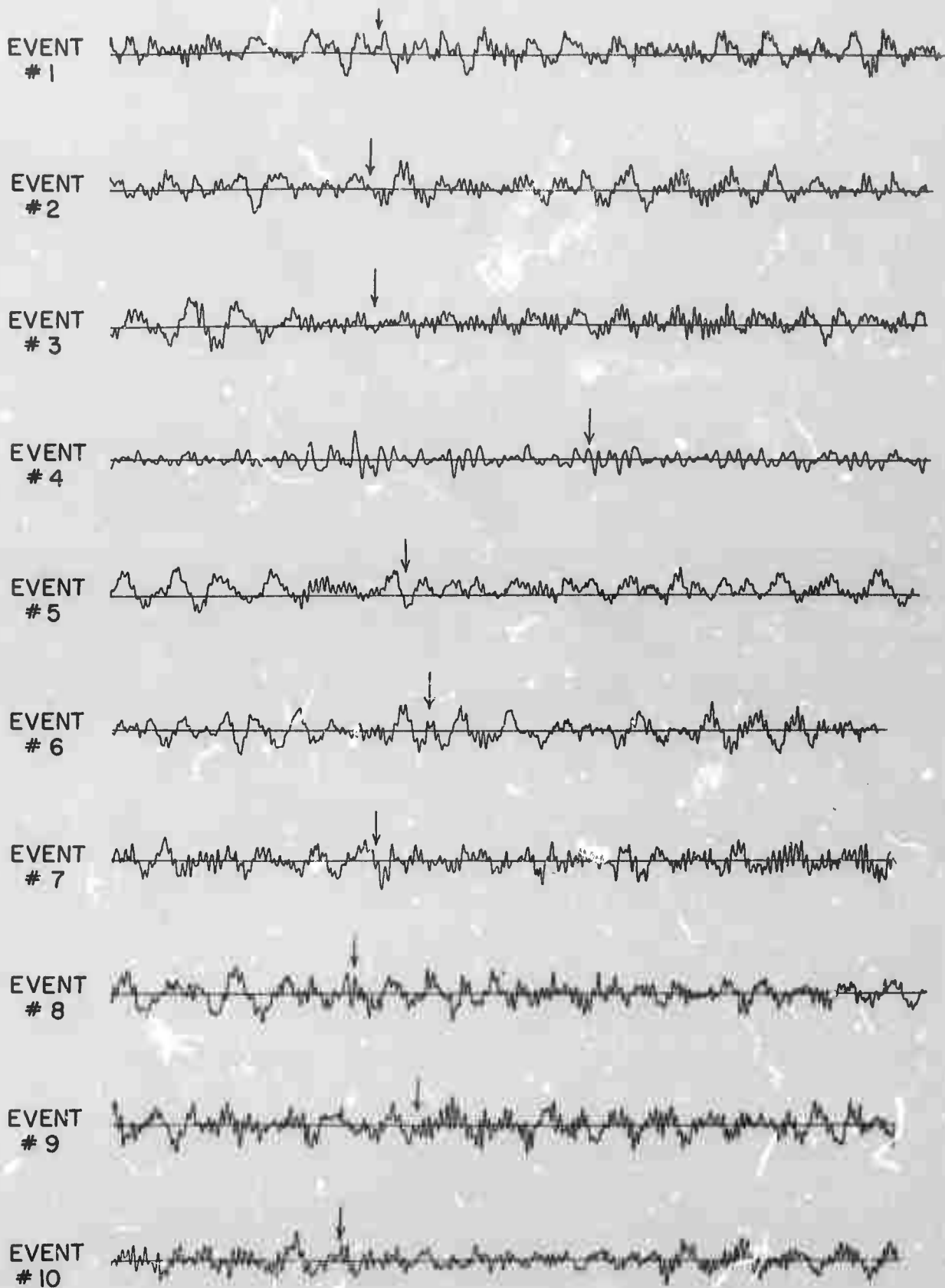


Figure V. Surface Vertical Components (Unfiltered)

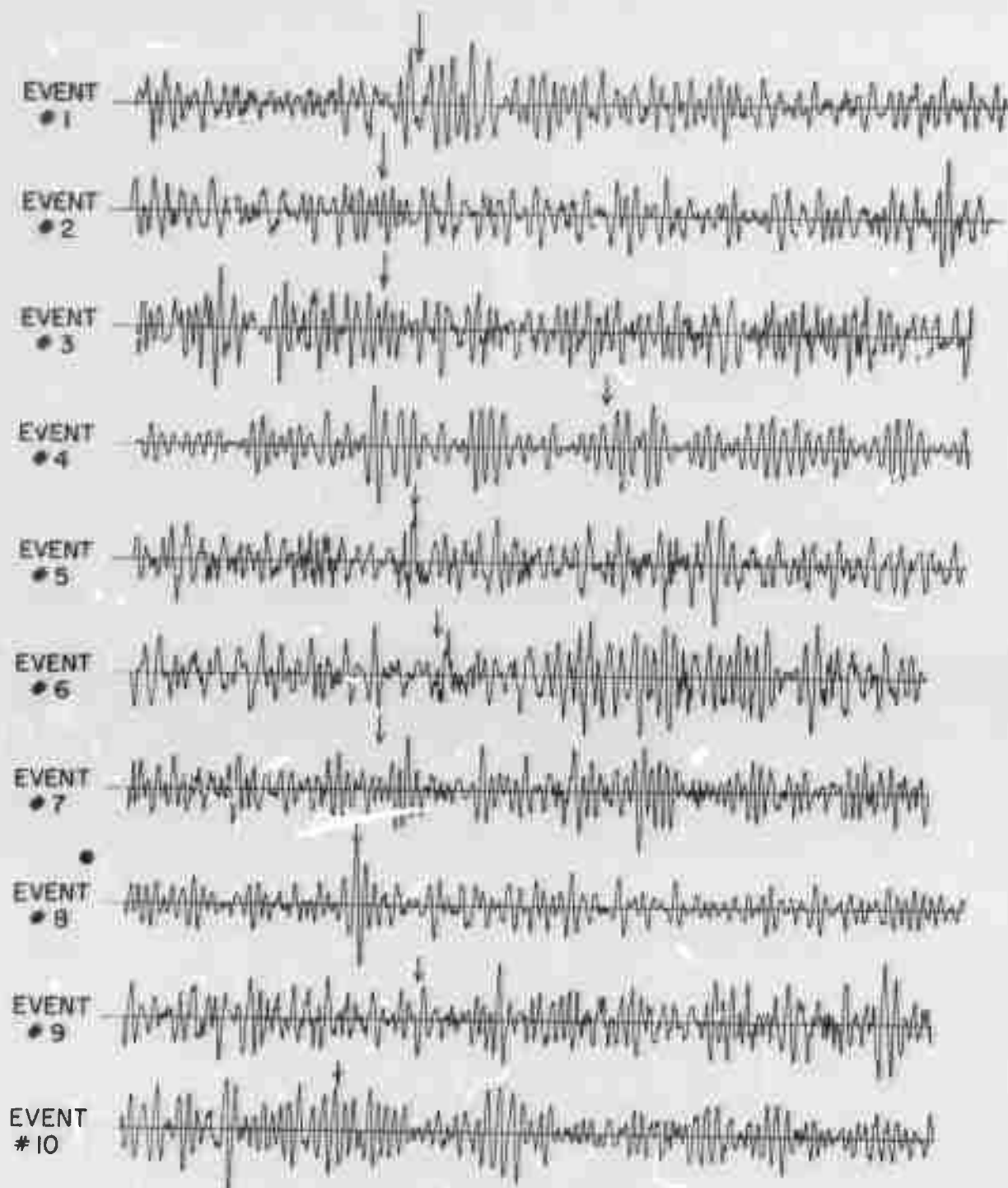


Figure V-1. Surface Vertical Components (Filtered)

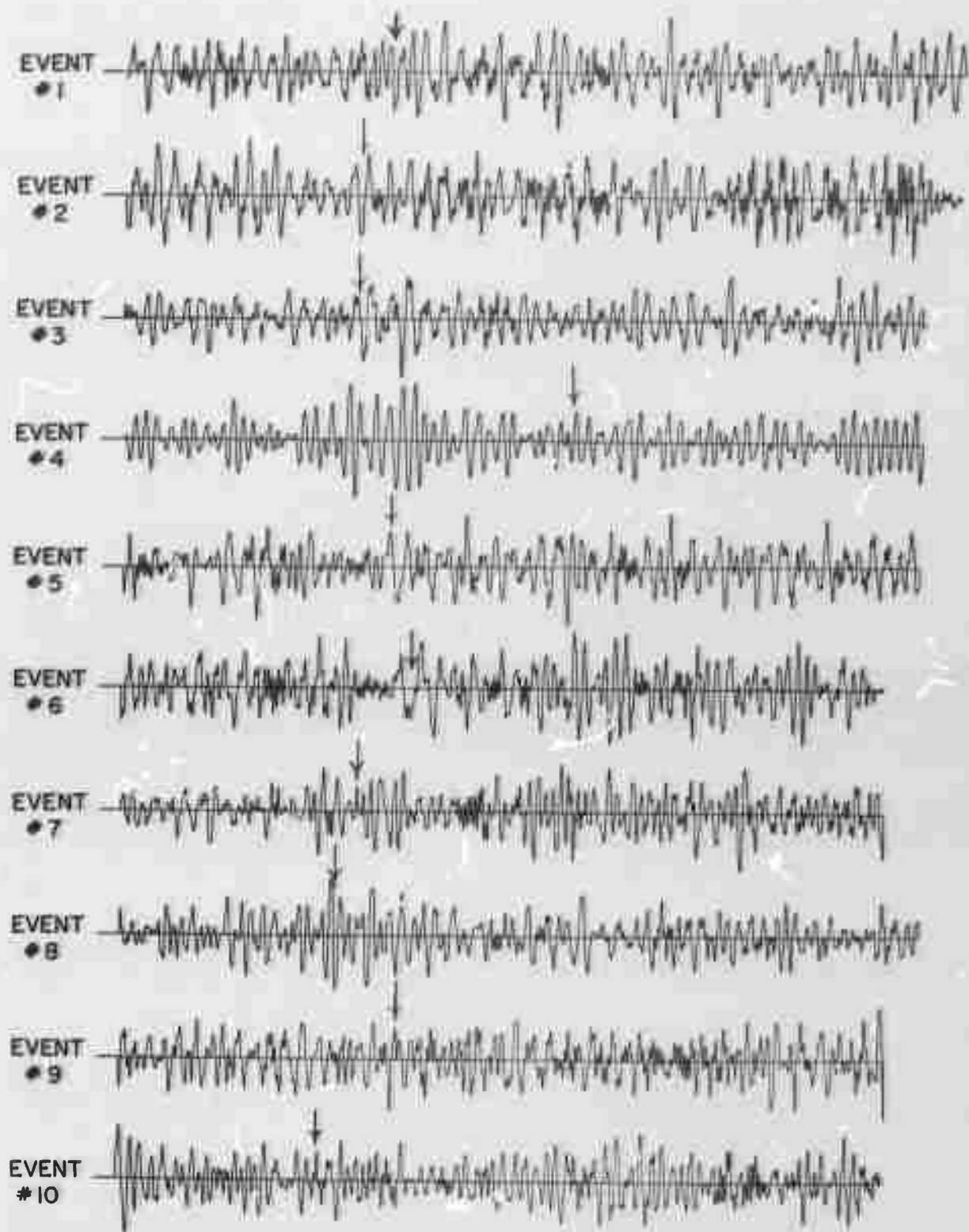


Figure VI. Filtered Phased Deghosted Sum Traces

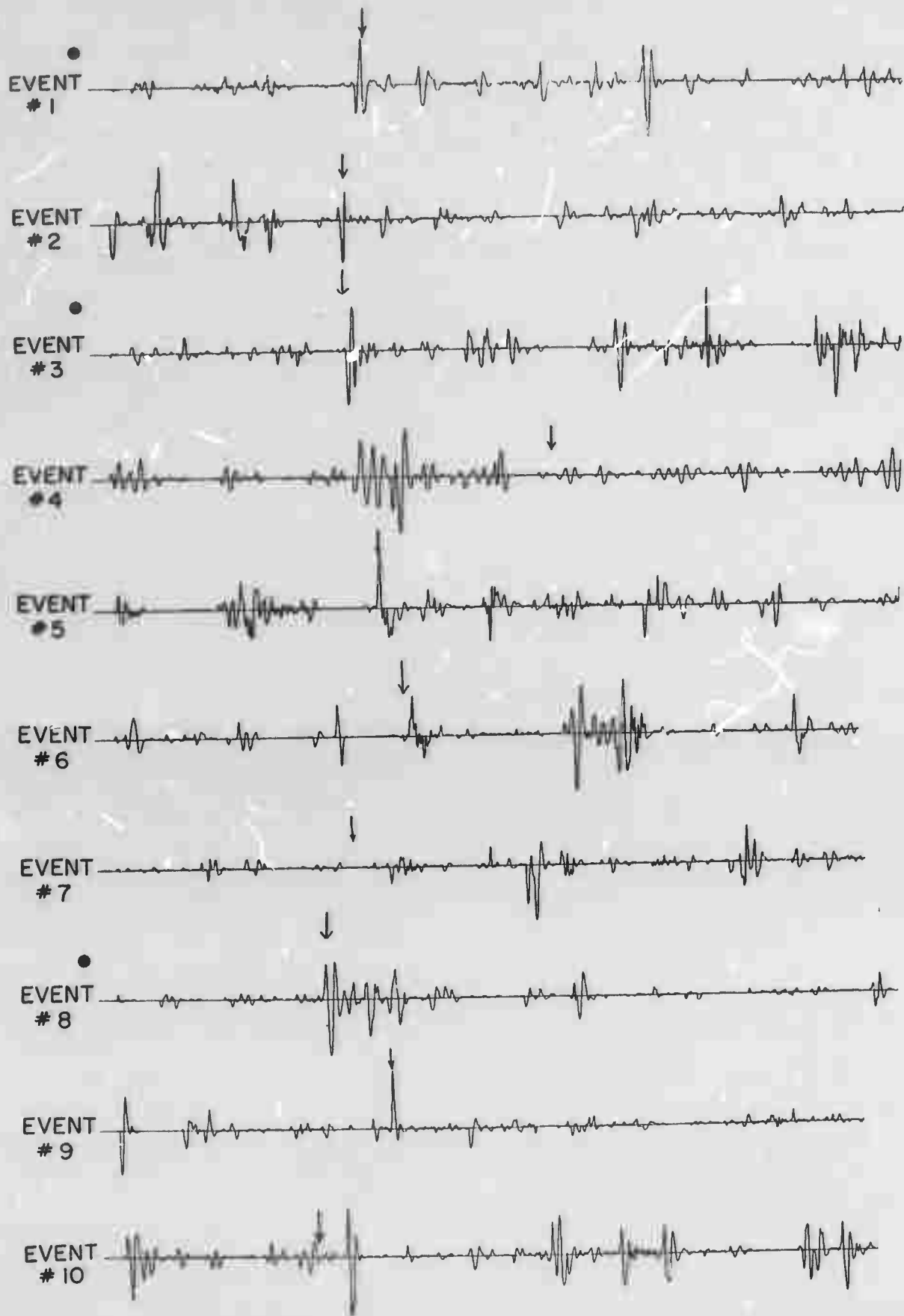


Figure VII. Filtered Phased Deghosted Correlation Traces

results suggest some improvement is probable. Both deghosting methods work well, the inverse deghosting operator favored as it does not require exact control of the gain on all instruments and does not require a quiet surface recording. The correlation traces used for detecting the upgoing P-pulses impose the strongest possible requirement that the signal be fixed jointly on all channels. For zero lags, the processing time is approximately  $3/4$  minutes per minute of data for all five elements of the vertical array. Similarly, using lags, the processing time is approximately  $1\frac{1}{2}$  minutes per minute of data.



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## APPENDIX I

### Deghosting, Method II

First, obtain the forward operation Z-transform which generates the deepwell trace from the surface trace

$$D(t) = \frac{1}{2} S\left(t + \frac{t_0}{2}\right) + \alpha S\left(t - \frac{t_0}{2}\right)$$

The reflection coefficient is  $\alpha$ , and two-way echo time is  $t_0$ . The basic shift-time unit for purpose of the Z-transform is  $t_0$ .

$$D(Z) = \frac{1}{2} (Z^{-\frac{1}{2}} + \alpha Z^{+\frac{1}{2}}) S(Z)$$

$$\frac{1}{2} S(Z) = \frac{Z^{\frac{1}{2}} D(Z)}{1 + \alpha Z}$$

$$= \left[ Z^{\frac{1}{2}} D(Z) \right] \left[ 1 - \alpha Z + \alpha^2 Z^2 - \dots \right]$$

The  $Z^{\frac{1}{2}}$  means shift one half the echo time before or after performing the right hand infinite sequence of operations. These operations involve successive scale factoring, shifting, and adding or subtracting as indicated. The stability of the operation under noise and speed of convergence is improved by re-arrangement of the operations as follows:

$$\begin{aligned} \left[ 1 - \alpha Z + \alpha^2 Z^2 - \dots \right] &= \left[ (1 - \alpha Z) + \alpha^2 Z^2 (1 - \alpha Z) \right. \\ &\quad \left. + \alpha^4 Z^4 \left\{ (1 - \alpha Z) + \alpha^2 Z^2 (1 - \alpha Z) \right\} + \dots \right] \end{aligned}$$

Note that each iterative shift operation on the right side doubles the interval between the ghost reflection and primary rather than increasing it linearly as on the left side so that, term by term, the recursive formula on the right side converges much faster. The factor of gain in processing time is  $(\log_2 N)/N$  or about 100 for a one-minute record at 20 points/second. In the time domain, the above operator can be expressed as a recursive filter.

$$\phi_1(t) = D(t) - \alpha D(t - t_0)$$

$$\phi_{j+1}(t) = \phi_j(t) + \alpha^k D(t - kt_0)$$

$$k = 2^j \quad (j = 1, 2, \dots, J)$$

and  $J t_0 < T$  where  $T$  is total record length in seconds.

$$\frac{1}{2} S(t + t_0/2) = \phi_J(t)$$

## APPENDIX II

### Estimate of the Jointly Correlated Signal from Multi-Channel Records

The minimum variance estimate of the co-linear component on two time series for complex signals is taken from Mason and Zimmerman (1960). The energy is defined as the squared magnitude of the signal. The correlation coefficient is a complex number designating the amplitude ratio and phase (or time) shift between the two signals. For the integrated square of the residuals, we find the energy integral

$$\begin{aligned} \int \left| v_1 - c_{12} v_2 \right|^2 dt &= \int (v_1 - c_{12} v_2) (v_1^* - c_{12}^* v_2^*) dt \\ &= \int \left| v_1 \right|^2 dt - 2 \operatorname{Re} \left[ c_{12}^* \int v_1 v_2^* dt + \left| c_{12} \right|^2 \int \left| v_2 \right|^2 dt \right] \end{aligned}$$

Re designates real part and asterisk, complex conjugation. The middle integral on the right is a complex number and may be expressed in polar form

$$\int v_1 v_2^* dt = A e^{j\theta}$$

We adjust the magnitude and polar angle of  $c_{12}$  to minimize the energy integral. The optimum angle for  $c_{12}$  is  $\theta$ ,

$$c_{12} = \left| c_{12} \right| e^{j\theta}$$

Substituting in the energy integral

$$\int (v_1 - c_{12} v_2)^2 dt = \int \left| v_1 \right|^2 dt - 2 \left| c_{12} \right| A$$

We minimize the energy by adjustment of the magnitude of  $C_{12}$

$$\frac{\partial}{\partial C_{12}} \int |v_1 - C_{12} v_2|^2 dt = -2A + 2|C_{12}| \int |v_2|^2 dt = 0$$

$$|C_{12}| = \frac{A}{\int |v_2|^2 dt}$$

Multiplying both sides by  $e^{j\theta}$

$$C_{12} = \frac{\int v_1 v_2^* dt}{\int |v_2|^2 dt}$$

If the signals are pulses imbedded in noise on the two channels of pulsewidth  $T$ , we may choose to replace the above integration by an average or summation restricted to a time window  $T$ , symbolized as  $\langle \rangle$ . For this case we use a moving time-window for estimating  $C_{12}$  at each point along the time series

$$C_{12}(t) = \frac{\int_{-T/2}^{+T/2} v_1(t' - t) v_2^*(t' - t) dt'}{\int_{-T/2}^{+T/2} |v_2(t' - t)|^2 dt'} = \frac{\langle v_1 v_2^* \rangle}{\langle |v_2|^2 \rangle}$$

For a signal which is aligned or linearly polarized on the two channels, we can take the signal as real in which case  $v_2^* = v_2$ . For case where the signal is band-limited and

imbedded in broad-band noise we compute the correlation coefficient with lags.

$$C_{12}(t, \tau) = \frac{\int_{-T/2}^{+T/2} v_1(t' - t) v_2^*(t' - t - \tau) dt'}{\int_{-T/2}^{+T/2} |v_2(t' - t)|^2 dt'} = \frac{\langle v_1 \otimes v_2^* \rangle}{\langle |v_2|^2 \rangle}$$

If the signal is both band-limited and linearly polarized on the two components,

$$C_{12}(t, \tau) = \frac{\int_{-T/2}^{+T/2} v_1(t' - t) [v_2^*(t' - t - \tau) + v_2^*(t' - t + \tau)] dt'}{\int_{-T/2}^{+T/2} |v_2(t' - t)|^2 dt'}$$

$$= \frac{\langle v_1 \otimes (v_2^* + v_2) \rangle}{2 \langle |v_2|^2 \rangle}$$

Generally, a better estimate of an imbedded signal can be obtained if the co-ordinates  $v_1$  and  $v_2$  are rotated to  $v_1'$  and  $v_2'$ . The rotation which maximizes S/N ratio is given by Sax (1966). The operator  $C_{12}$  is used as a time varying filter to extract an estimate of  $v_1$  from  $v_2$ .

$$\hat{v}_1 = c_{12} \otimes v_2$$

or it can be used as a gain control voltage to estimate the imbedded signal.

$$\hat{v}_{1(t)} = c_{12}(t) v_2(t)$$

If preferred, the Wiener criteria is used to estimate the signal

$$\hat{v}_1(t) = \frac{\langle v_1 v_2 \rangle}{(\langle |v_1|^2 \rangle \langle |v_2|^2 \rangle)^{\frac{1}{2}}} v_1(t)$$

and similarly as before with lags, we replace products in the numerator by convolutions.

For the multi-channel case, we have a fixed signal imbedded in N noise channels. We ask that the signal be jointly correlated on all channels. As a fast method for measuring the jointly correlated signal, we make a chained estimation of the  $v_1(t)$  on the N channels as follows for the zero lag case.

The minimum variance estimate of  $v_1$  from  $v_2$  is

$$\hat{v}_{1,2}(t) = \frac{\langle v_1 v_2 \rangle}{\langle |v_2|^2 \rangle} v_2$$

of  $v_1$  from  $v_2$  and  $v_3$  is

$$\hat{v}_{1,(2,3)} = \frac{\langle \hat{v}_{1,2} v_3 \rangle v_3}{\langle |v_3|^2 \rangle} = \frac{\langle \langle v_1 v_2 \rangle v_3 \rangle}{\langle |v_2|^2 \rangle \langle |v_3|^2 \rangle} v_3$$

and  $v_1$  from  $v_2, v_3, \dots, v_N$

$$\hat{v}_{1,(2, \dots, N)} = \frac{\langle \dots \langle \langle v_1 v_2 \rangle v_3 \rangle \dots \rangle v_N}{\langle |v_2|^2 \rangle \langle |v_3|^2 \rangle \dots \langle |v_N|^2 \rangle} v_N$$

and with lags (including zero lag as a special case)

$$\hat{v}_{1,(2, \dots, N)} = \frac{\langle \dots \langle \langle v_1 \otimes v_2 \rangle \otimes v_3 \rangle \dots \otimes v_N \rangle}{\langle |v_2|^2 \rangle \langle |v_3|^2 \rangle \dots \langle |v_N|^2 \rangle} v_N$$

2  
This is one of the operators used in this report. For the case of lags we replace the products in the numerator by convolutions, but practical time of computation considerations alone rule out anything but a small number of lags. Note in the above formula that  $\hat{v}$ , is estimated from  $v_N$  which may be selected from any of the available channels. The correlation is most useful if all of the channels are approximately the same quality, and the channel selected for  $v_N$  should be the best available; in our case, this is the surface seismogram. If the seismograms are of widely varying quality, the above formula should be generalized to include rotation and a test to eliminate bad channels. Since by hypothesis we require correlation on all channels, we also observe that it is not necessary to consider correlations on all possible pairs of sensors, resulting in considerable time savings in the calcu-



lation of the correlation trace. The correlation  $\hat{v}_1(2, \dots, N)$  may be generalized to include lags.

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